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# Abstract

This report presents a procedure for estimating parametric probabilistic models of hurricane wind speeds from existing information on estimated wind speeds with various mean recurrence intervals (MRIs). Such models may be needed, for example, for the estimation of hurricane wind speeds with long MRIs required for the performance-based design of structures susceptible of experiencing nonlinear behavior. The report first describes the procedure as applied to the case where that information is obtained from ASCE 7-10 wind maps, and provides examples of its application to a number of coastal mileposts on the Gulf and Atlantic coasts. Next, the procedure is applied by using, in addition to the ASCE 7-10 information, hurricane wind speeds with 1,000,000- and 10,000,000-year MRIs estimated in a 2011 Nuclear Regulatory Commission report. It is then argued that ASCE 7-10 Standard basic wind speeds for New York City are unconservative with respect to their counterparts specified in the Standard for other U.S. hurricane-prone locations. Finally, best fitting extreme value distributions of hurricane wind speeds were found to have finite upper tails of the reverse Weibull type, rather than infinite upper tails of the Gumbel type. This result may help to change the still widely held belief that extreme wind speeds are appropriately modeled only by the Gumbel distribution.

**Keywords:** Extreme values; hurricanes; New York City wind climate; risk consistency; wind engineering; wind speeds.

# Acknowledgements

The authors are indebted to K. Emanuel of the Massachusetts Institute of Technology and to C. Landsea of the National Hurricane Center, for helpful discussions; to P.J. Vickery for providing estimates of hurricanes wind speeds for the locations indicated in the report; to N. A. Heckert of the Statistical Engineering Division, National Institute of Standards and Technology, for valuable statistical advice; and to F.T. Lombardo and M.L. Levitan for useful comments.

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# 1. Introduction

Estimates of probability distributions of extreme wind speeds can be useful in a variety of applications, in particular within the context of performance-based design. Parametric probabilistic models for wind speeds in non-hurricane-prone regions of the U.S. are available, and one such model has been used to develop the wind speed maps specified in the ASCE 7-10 Standard (ASCE 2010) for the conterminous United States. However, no parametric models are available in the literature for the description of proprietary sets of simulated hurricane wind speeds used to estimate the basic wind speeds specified in the Standard for hurricane-prone regions. Rather, the estimation of those speeds as functions of various Mean Recurrence Intervals (MRIs) has been performed by applying (a) non-parametric statistics to synthetic data obtained from the numerical simulation of hurricanes and tropical storms, and (b) the ASCE 7-10 probabilistic model of non-hurricane wind speeds. For details see Vickery et al. (2010).

# 2. Procedure for Estimating Distributions of Hurricane Wind Speeds from Recent Information in the Public Domain

## 2.1 *Estimation of Probability Distributions of Hurricane Wind Speeds from ASCE 7-10 Wind Speed Maps.*

Basic wind speeds for hurricane-prone regions specified in the ASCE 7-10 Standard were estimated by accounting for both non-hurricane and hurricane (including tropical storm) winds (Vickery et al. 2010). This was done by using the expression

$$P(v_{NH} \leq V \text{ and } v_H \leq V) = P(v_{NH} \leq V)\, P(v_H \leq V) \quad (1)$$

where $P$, $v_{NH}$, and $v_H$ denote cumulative distribution function (CDF), non-hurricane wind speed, and hurricane wind speed, respectively. The left-hand side of Eq. 1 is called the mixed distribution of the non-hurricane and hurricane wind speeds.

The probabilistic model for non-hurricane wind speeds assumed in ASCE 7-10 for the entire conterminous United States with the exception of California, Oregon, Washington, and a few isolated special wind regions is a Type I (Gumbel) Extreme Value distribution that, for 50-, 100-, 300-, 700-, and 1,700-year MRI, yields 89.9, 96.2, 106.2, 113.9, and 122 mph 3-s extreme peak gust speeds at 10 m above open terrain, respectively (these values were rounded in ASCE 7-10 to 90, 96, 105, 115, and 120 mph, respectively, see Vickery et al. 2010). The Gumbel distribution parameters yielding those values were estimated in this work to be $\mu = 54.3$ mph (location parameter) and $\sigma = 9.1$ mph (scale parameter). For a specified wind speed $V$ with mean recurrence interval $N$,

$$P(V) = 1 - 1/N(V). \quad (2a)$$

Equation 2a allows results to be expressed either in terms of CDF ordinates or in terms of MRIs; that is, to any specified value of $P(V)$ there corresponds an MRI $N$ of the velocity $V$, given by the expression

$$N(V) = 1/[1 - P(V)] \quad (2b)$$

The ASCE 7-10 wind maps provide the wind speeds $V$ corresponding to the ordinates of the mixed non-hurricane and hurricane wind speed distribution $P(v_{NH} \leq V$ and $v_H \leq V)$ with the 50-, 100-, 300-, 700-, and 1,700-year MRIs. Since the estimated Gumbel distribution of the non-hurricane wind speeds is known, it is possible to calculate the ordinates of the probability distribution $P(v_{NH} \leq V)$ corresponding to those MRIs. Therefore $P(v_H \leq V)$ can be obtained from Eq. 1. For example, in Fig. 1, for $V = 97$ mph and $N = 50$ years, $P(v_{NH} \leq V$ and $v_H \leq V) = 0.98$. For $V = 97$ mph, $P(v_{NH} \leq V)$ can be immediately obtained from the Gumbel distribution specified for non-hurricane winds in the ASCE 7-10 Standard with estimated parameters indicated in the preceding paragraph; the estimation of $P(v_H \leq V)$ then follows immediately from Eq. 1. This step is repeated for $N = 100$, 300, 700, and 1,700 years, yielding five estimated points of the CDF $P(v_H \leq V)$.

It is reasonable to assume that the hurricane wind speed distribution $P(v_H \leq V)$ is modeled appropriately by an Extreme Value (EV) distribution. There are three types of EV distributions: Fréchet, Gumbel, and reverse Weibull. It is well known that for long MRIs the Fréchet distribution typically yields unrealistically high velocities – of the order of thousands of miles per hour, – and should therefore not be used as a model of extreme wind speeds. The choice then remains between the Gumbel distribution

$$P(v_H \leq V) = \exp\left[-\exp\left(-\frac{v-b}{a}\right)\right] \qquad (-\infty<V<\infty;\ -\infty<a<\infty;\quad 0<b<\infty), \qquad (3)$$

which has infinite upper tail, and the reverse Weibull distribution

$$P(v_H \leq V) = \exp\left[-\left(-\frac{v-b}{a}\right)^{-\frac{1}{c}}\right] \qquad \text{for } V \leq b \qquad (4a)$$

$$P(v_H \leq V) = 1 \qquad \text{for } V > b, \qquad (4b)$$

which has limited upper tail. (The parameters $a$ and $b$ are called the scale and location parameter, respectively; in the reverse Weibull distribution the parameter $c$ is called the tail length parameter.)

First, parameters for the Gumbel and reverse Weibull distributions that best fit the ordinates of $P(v_H \leq V)$ were estimated by using a nonlinear least squares fitting method (see http://www.itl.nist.gov/div898/software/dataplot/refman1/auxillar/orthdist.htm for details) for three sets of simulated hurricane wind speed data sets used to develop ASCE 7-10 and NRC wind maps. The sets were kindly provided to the authors by Vickery (2012) for Miami, Fl. (latitude 25.85° N; longitude 80.12° W), Long Island, NY (latitude 40.58° N; longitude 73.15° W ), and Maine (latitude 44.60° N; longitude 67.45° W) following a request by Simiu, Lombardo and Yeo (2012). For these sets the average residual standard deviations per data point were found to be, respectively, 4.5, 4.3, and 19.4 for the reverse Weibull distribution, and 6.8, 6.3, and 788.5, for the Gumbel distribution; that is, in each of these cases the fit was better for the reverse Weibull than for the Gumbel distribution.

The procedure based on Eq. 1 described earlier was then applied to five locations: Boston, Mass., Ocean City, Md., Miami Beach, Fl., Biloxi, Miss., and Galveston, Tex. The parameters of the reverse Weibull distributions that best fit the ordinates of $P(v_H \leq V)$, estimated on the basis of the ASCE 7-10 information, are shown in the first three columns of Table 1. Figures 1 through 5 show the estimated distributions of $v_H$ as functions of MRI, based on the the fitting procedure just described and the ASCE 7-10 information. Those figures also show the estimated mixed distributions of $v_H$ and $v_{NH}$, as well as the distributions of $v_{NH,}$ as functions of MRI.

Table 1. Estimated reverse Weibull distribution parameters.

| | ASCE 7-10 | | | ASCE 7-10 and NRC | | |
|---|---|---|---|---|---|---|
| | *c* | *b* [mph] | *a* [mph] | *c* | *b* [mph] | *a* [mph] |
| Boston, MA | -0.047 | 416.82 | 397.19 | -0.214 | 179.56 | 218.05 |
| Ocean City, MD | -0.064 | 318.44 | 299.27 | -0.152 | 199.13 | 209.63 |
| Miami Beach, FL | -0.092 | 323.15 | 278.54 | -0.097 | 317.59 | 276.74 |
| Biloxi, MS | -0.115 | 301.30 | 292.49 | -0.121 | 294.04 | 287.71 |
| Galveston, TX | -0.093 | 273.59 | 227.85 | -0.059 | 343.38 | 286.51 |

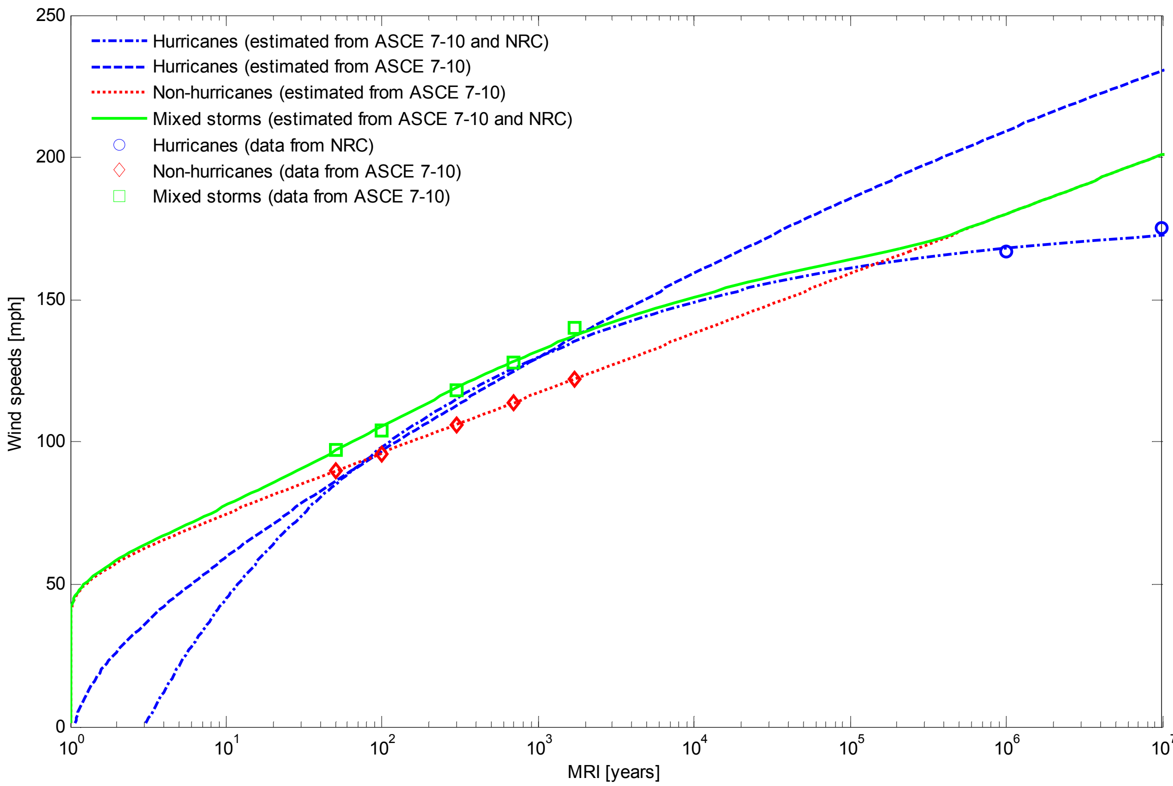


Figure 1. Wind speed distributions of storms as a function of MRI (Boston, Ma.)

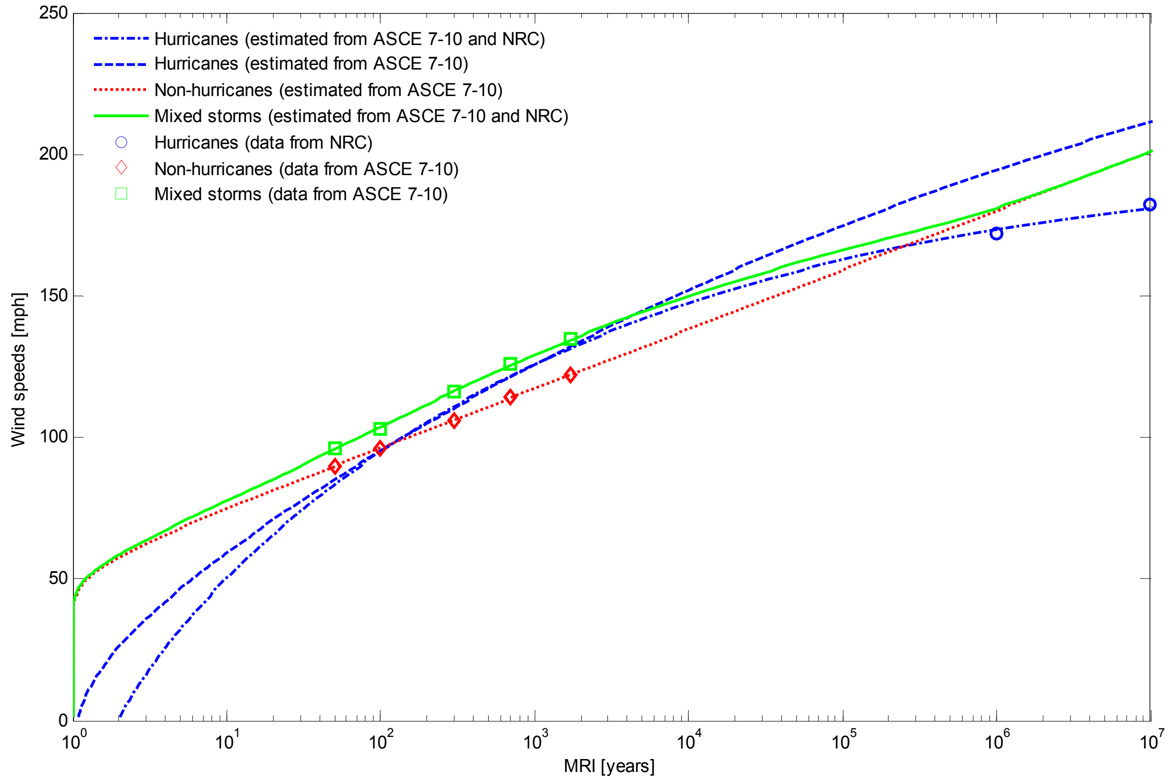


Figure 2. Wind speed distributions of storms as a function of MRI (Ocean City, Md.)

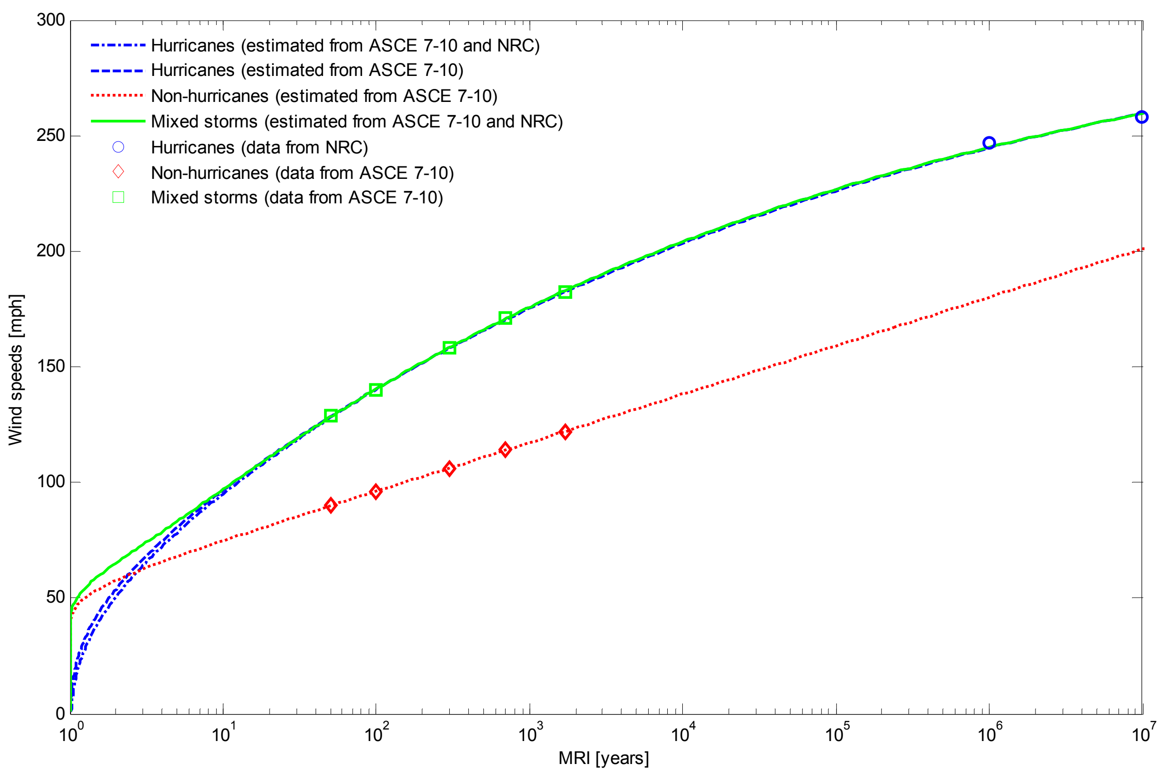


Figure 3. Wind speed distributions of storms as a function of MRI (Miami Beach, Fl.)

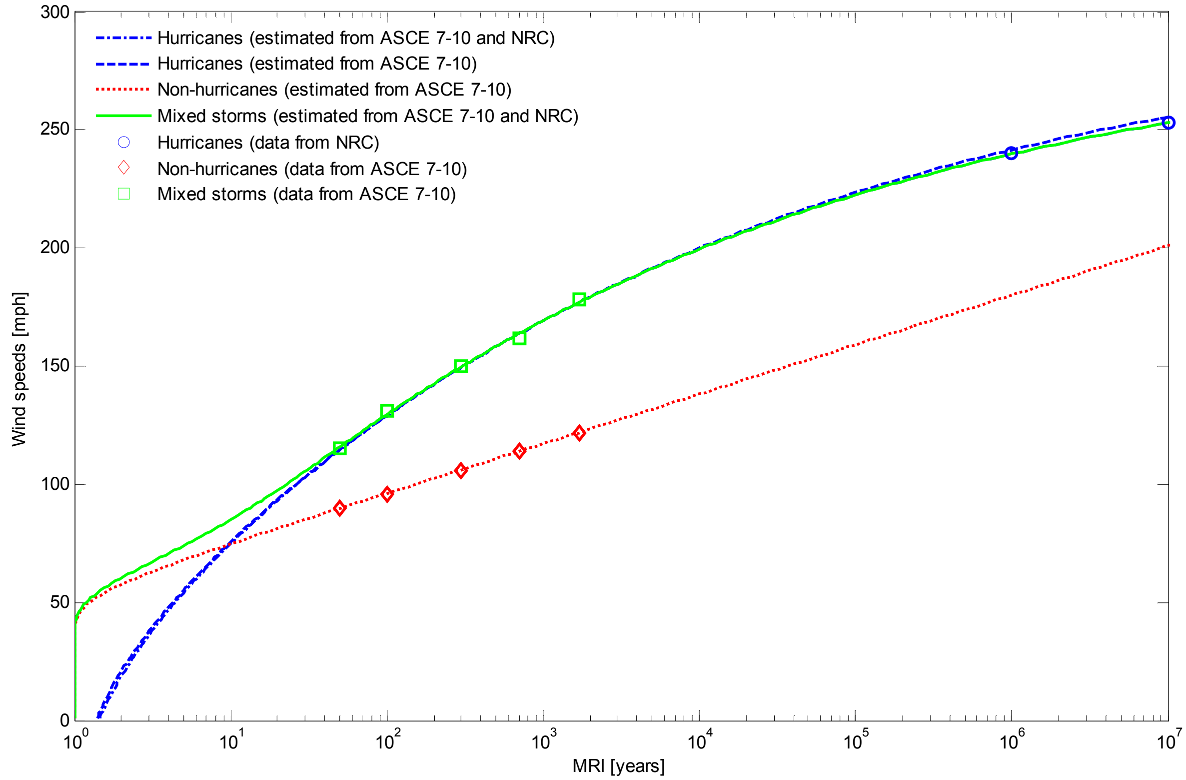


Figure 4. Wind speed distributions of storms as a function of MRI (Biloxi, Ms.)

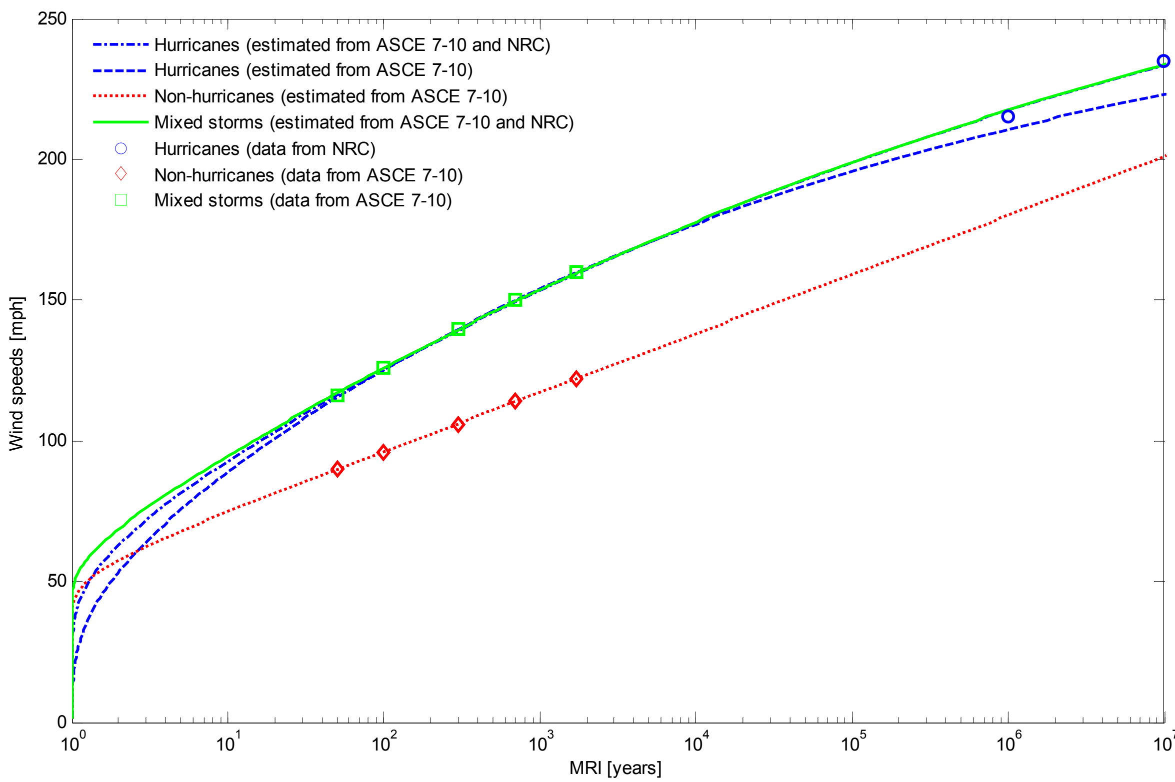


Figure 5. Wind speed distributions of storms as a function of MRI (Galveston, Tx.)

## 2.2 *Estimation of Probability Distributions of Hurricane Wind Speeds from ASCE 7-10 and NRC Wind Speed Maps.*

In addition to the distributions of $v_H$ estimated by using the ASCE 7-10 information, Figs. 1 through 5 show those distributions based on both the ASCE 7-10 information and the estimates of hurricane wind speeds reported in the NRC report mentioned earlier. For Miami Beach, Fl. and Biloxi, Ms. (Figs. 3 and 4) the two distributions are indistinguishable from each other for all MRI between 50 and 10,000,000 years; in other words, with no loss of precision, the 10,000,000-year hurricane wind speed can be estimated only from the ASCE 7-10 information on 50-, 100-, 300-, 700-, and 1,700-year wind speeds. This is also in practice true for Galveston, Tx, where the difference between the two distributions for the 10,000,000-year MRI is about 5 %. However, that difference is about 25 % for Boston, and about 14 % for Ocean City, Md. This is tentatively ascribed to larger errors due to the relative infrequency of hurricane occurrences at these locations. The parameters of the reverse Weibull distribution based on the ASCE 7-10 Standard and the NRC report are listed in the last three columns of Table 1.

Note that the probabilistic modeling of the radius of maximum wind speeds, $r_m$, and of the central pressures, $p_c$, was different for the simulations performed for the ASCE 7-10 on the one hand and the NRC estimates on the other. For the former it was assumed that the lowest possible values of $r_m$ and $p_c$ are 8 km and 863 hPa, respectively; for the latter, that they are 4 km and 823 hPa, respectively, meaning that the probabilistic model assumed for the NRC simulations was more conservative than the ASCE 7-10 model. Nevertheless, both for Boston and Ocean City the more conservative model yields *lower* estimates of the 10,000,000-year hurricane speeds, rather than higher estimates, as would be expected.

The estimated plots of Figs. 1 through 5 can be used, among other purposes, for estimating hurricane wind speeds with MRIs larger than 1,700 years, which may be required for the performance-based design of various types of structures, including structures susceptible of experiencing nonlinear behavior under exceptionally strong windstorm events, or for the design of Liquid Natural Gas (LNG) facilities, required by Federal regulations to be designed for MRIs of at least 10,000 years (http://ecfr.gpoaccess.gov/cgi/t/ text/text-idx?c=ecfr&rgn=div5&view=text&node =49:3.1.1.1.9&idno=49#49:3.1.1.1.9.2.14.6, section § 193.2067 Wind forces, paragraph b2ii). In view of the public availability of the ASCE 7-10 and NRC sets of data it is recommended that both sets be used for estimating probability distributions of hurricane wind speeds.

## 2.3 *Estimates of Probability Distributions of Hurricane Wind Speeds Obtained Directly from Results of Simulations.*

Table 2 lists the Miami and Long Island simulated hurricane wind speeds corresponding to twenty MRIs from 50 to 10,000,000 years, provided to the authors by Vickery (2012), as indicated earlier. Based on these speeds the best fitting reverse Weibull distribution parameters were $a$ = 234.46 mph, $b$ = 262.29 mph, $c$= -0.134, and $a$ = 191.01 mph, $b$ = 194.81, and $c$= -0.133, respectively.

Table 2. Estimated hurricane wind speeds, in mph.

| MRI [year] | Miami (Vickery, 2012) | Long Island (Vickery, 2012) | Long Island (based on Lin and Chavas, 2012) | New York City (based on Lin and Chavas, 2012) |
|---|---|---|---|---|
| 50 | 124 | 78 | 85 | 81 |
| 100 | 136 | 90 | 98 | 92 |
| 300 | 154 | 106 | 114 | 104 |
| 700 | 165 | 117 | 125 | 111 |
| 1,700 | 175 | 125 | 134 | 120 |
| 10,000 | 193 | 139 | 149 | 130 |
| 100,000 | 214 | 152 | 162 | 139 |
| 1,000,000 | 228 | 160 | 171 | 144 |
| 10,000,000 | 233 | 179 | 177 | 148 |

# 3. Estimates of Basic Wind Speeds for New York City

According to the ASCE 7-10 wind maps, basic wind speeds with 50-, 100-, 300-, 700-, and 1,700-year MRI are practically the same for New York City as for any non-hurricane location within the conterminous U.S., with the exceptions noted earlier of California, Oregon and Washington and of special wind regions with complex orographic features. Implicit in these maps is the statement that the effect of hurricanes on New York City's extreme wind climate is nil. For example, according to ASCE 7-10, for non-hurricane wind speeds with a 700-year MRI $P(v_{NH} \leq 115 \text{ mph}) = 0.99857$, while for hurricane or non-hurricane wind speeds with a 700-year MRI $P(v_{NH} \leq 115 \text{ mph and } v_H \leq 115 \text{ mph}) = 0.99857$ as well. It then would follow from Eq. 1 that $P(v_H \leq 115 \text{ mph}) = 1$, meaning that the probability that hurricane wind speeds exceed 115 mph is zero. The approach presented in the preceding section is therefore inapplicable for New York City.

Hurricane wind speeds that may affect New York City could in fact be significant. The hurricane wind speed data used for estimating New York City basic wind speeds in the ASCE 7-10 wind maps are proprietary and were not available to the writers. However, we estimated New York City (southern tip of Manhattan) winds with various MRIs using wind data generated by Lin and Chavas (2012) based on the model developed by Emanuel et al. (2006). (The data were transformed from 10-min speeds at 10 m over water to 3-s peak gust speeds at 10 m over open terrain – see Simiu, 2011, p. 126). The best fitting parameters of the reverse Weibull distribution were $a = 162.36$ mph, $b = 159.88$ mph, and $c = -0.190$. Hurricane wind speeds estimated directly by using the model are listed in Table 2 for various MRIs.

For $v_H = 115$ mph the Emanuel et al. (2006) model yielded a 1,160-year MRI, Therefore, $P(v_H \leq 115 \text{ mph}) = 1 - 1/1{,}160 = 0.99914$, so by Eq. 1 $P(v_{NH} \leq 115 \text{ mph and } v_H \leq 115 \text{ mph}) = 0.99857 \times 0.99914 = 0.99771$, corresponding to an MRI of the 115 mph speed of $1/(1\text{-}0.99771) = 435$ years, which is closer to the MRI specified by ASCE 7-10 for, e.g., cowsheds, rather than for residential and commercial buildings. It can be verified that to correspond to the intended 700-year MRI, basic wind speeds specified for New York City should be 119 mph (or a rounded-up value of 120 mph), rather than 115 mph (or 114 mph, as indicated in Table C26.5-3 of ASCE 7-10's Commentary under the entry "Manhattan").

It was pointed out to the authors that the hurricane hazard is stronger for Long Island than for New York City "because, for the right front quadrant of the hurricane, where winds are typically strongest, to be over New York City would require the eye to be to the west of the city and follow a substantial trajectory over land, thus considerably reducing the wind speeds. Therefore, while the highest intensity possible thermodynamically for Long Island/New England may be near the border of Category 3-4 (≈130 mph 1-min speed), the worst possible hurricane for New York City would be substantially weaker - perhaps near the border of Category 2-3 (≈110 mph 1 min)" (Landsea 2012). This observation is borne out by the New York City and Long Island (latitude 40.58° N; longitude 73.15° W) hurricane wind speeds estimates of the last two columns of Table 2. It is also the case that Long Island was hit by a devastating hurricane in 1938, whereas the historical record does not include comparably powerful hurricanes affecting New York City. Nevertheless, as was shown earlier in this section, the Emanuel et al. (2006) model results in

New York City hurricane wind speeds that, unlike the Vickery et al. (2009) model results, are sufficiently strong to affect the estimation of basic design wind speeds.

Even though the modelers' knowledge and effort may be the best the state of the art allows, "however much evaluation may go into our models, they should not be accepted as truth, and *an engineer would be wise to build in a margin of error*" (Emanuel 2012). For example, in September of 1978, remedial work being performed on the inadequate structure of the Citicorp building in New York City had not yet been completed. As hurricane Ella was advancing northward from the Cape Hatteras area, two prominent, highly experienced structural engineers, W.J. LeMessurier and L. E. Robertson, as well as a prominent wind engineer, A.G. Davenport, expressed serious concern over the possibility that the hurricane might cause damage to or even cause the collapse of the Citicorp building (http://www.duke.edu/~hpgavin/ce131/citicorp1.htm). Luckily Ella bypassed New York City. However, dismissing the possibility of a hit would have been unacceptable. This was indeed the opinion of the structural engineers in charge, as well as the opinion of the wind engineers consulted in this case.

In 1974 the unusually strong hurricane Carmen was advancing due north toward New Orleans, and was expected to make landfall there, when at the last moment, owing to background winds that are not always easy to predict, its motion suddenly changed its direction from northward to westward. A change of direction – in this case an unfavorable change -- occurred in the path of hurricane Agnes (1972) as it was heading toward the coast north of New York City (see http://www.csc.noaa.gov/hurricanes). It is therefore conceivable that hurricanes could cross from the ocean into Manhattan through Brooklyn along a path roughly parallel to the path of hurricane Agnes, carrying winds with speeds possibly close to those that have affected Long Island in the past. This possibility is not reflected in current risk assessments and design criteria for New York City.

The considerations presented in this section indicate that the New York City basic wind speeds specified for the design of buildings and other structures in the ASCE 7-10 Standard are unconservative. A prudent description of extreme wind climatology should consider possibilities that have not been realized in the period of record available for analysis (see Emanuel et al., 2006), a period that is short compared to the MRIs of interest, and during which relatively few strong hurricanes have been observed.

# 4. Conclusions

This paper presents a procedure that makes it possible to obtain parametric probabilistic models for hurricane wind speeds implicit in the ASCE 7-10 wind maps. The paper first describes the procedure as applied to the case where that information is derived from ASCE 7-10 wind maps, and provides examples of its application to a number of coastal mileposts on the Gulf and Atlantic coasts. Next, the procedure is applied by using, in addition to the ASCE 7-10 information, hurricane wind speeds with 1,000,000- and 10,000,000-year MRIs estimated in a 2011 Nuclear Regulatory Commission report. It is then argued that ASCE 7-10 Standard basic wind speeds for New York City are unconservative with respect to their counterparts specified for other U.S. hurricane-prone locations. Finally, estimated best fitting extreme value distributions of hurricane wind speeds were found to have finite upper tails of the reverse Weibull type, rather than infinite upper tails of the Gumbel type. This result may help to change the still widely held belief that extreme wind speeds are appropriately modeled only by the Gumbel distribution.

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